Alternate Operating Scenarios for NDCX-II*

W M Sharp, A Friedman, D P Grote, R H Cohen, S M Lund, *LLNL*
J-L Vay, W L Waldron, *LBNL*

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Heavy Ion Fusion Science Virtual National Laboratory

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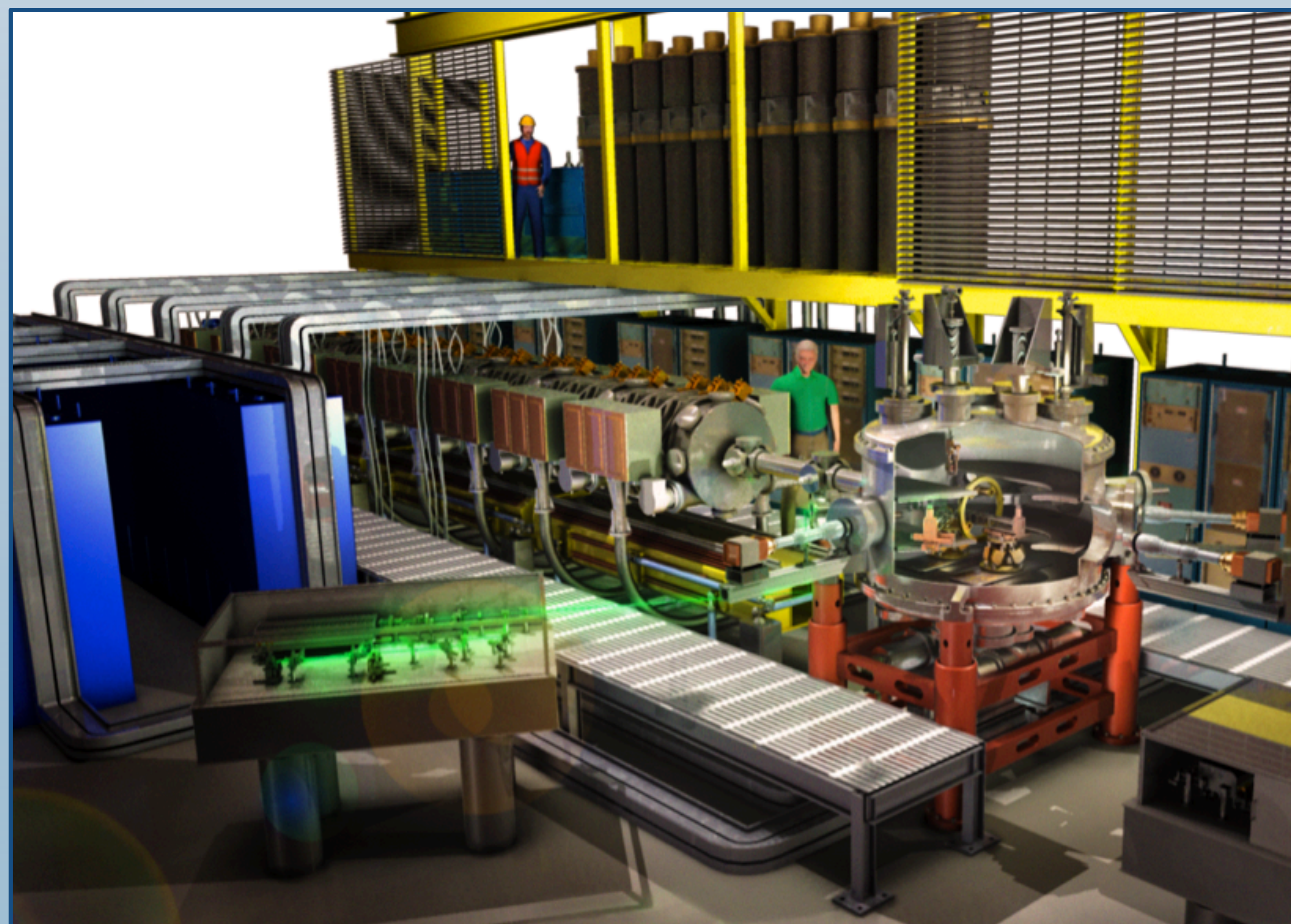
The NDCX-II project is complete

Livermore donated 50 induction cells from the ATA electron accelerator

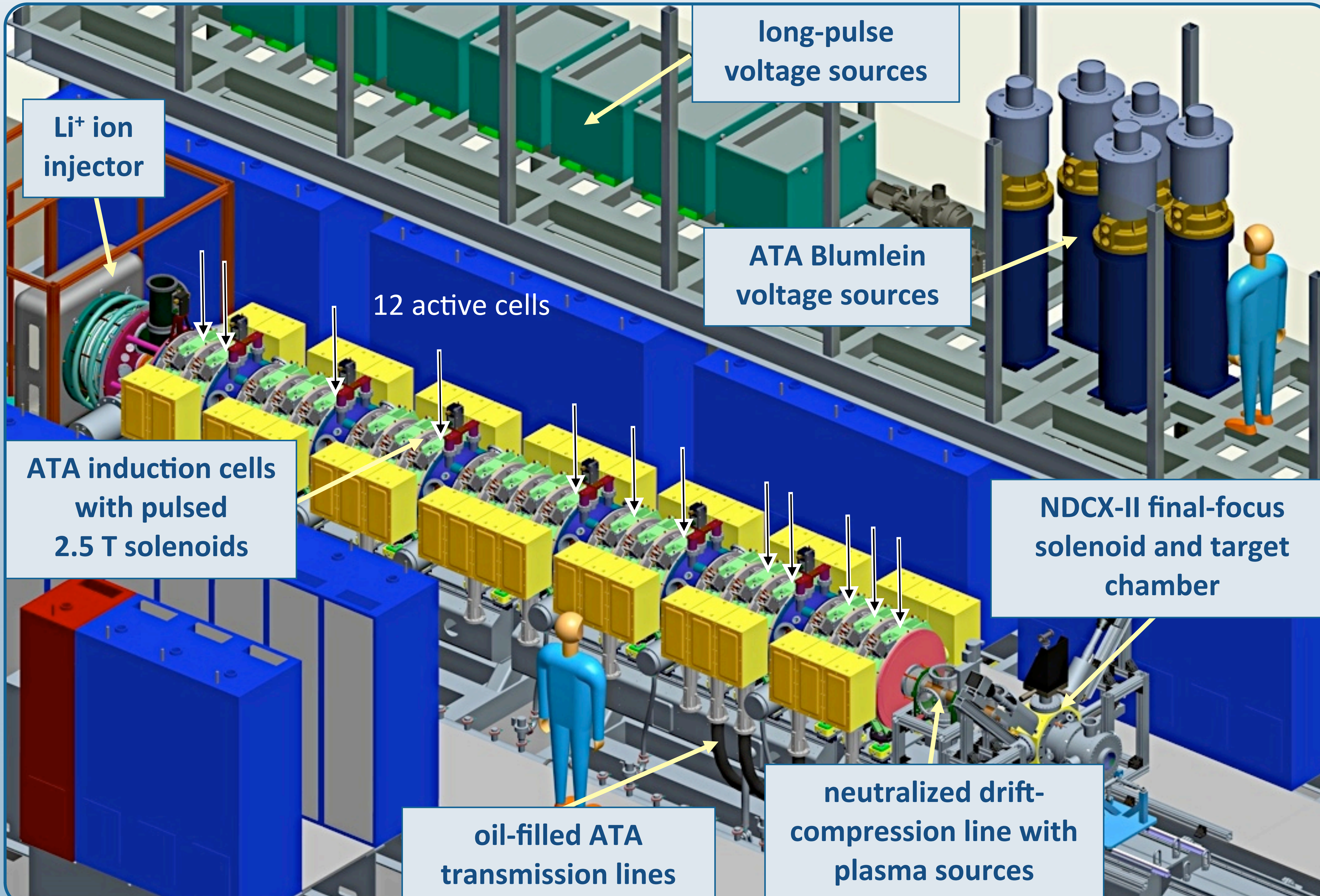
- ferrite cores each provide 1.4 x 10-2 Volt-seconds
- Blumlein voltage sources offer 200-250 kV with FWHM duration of 70 ns

project was completed in March 2012

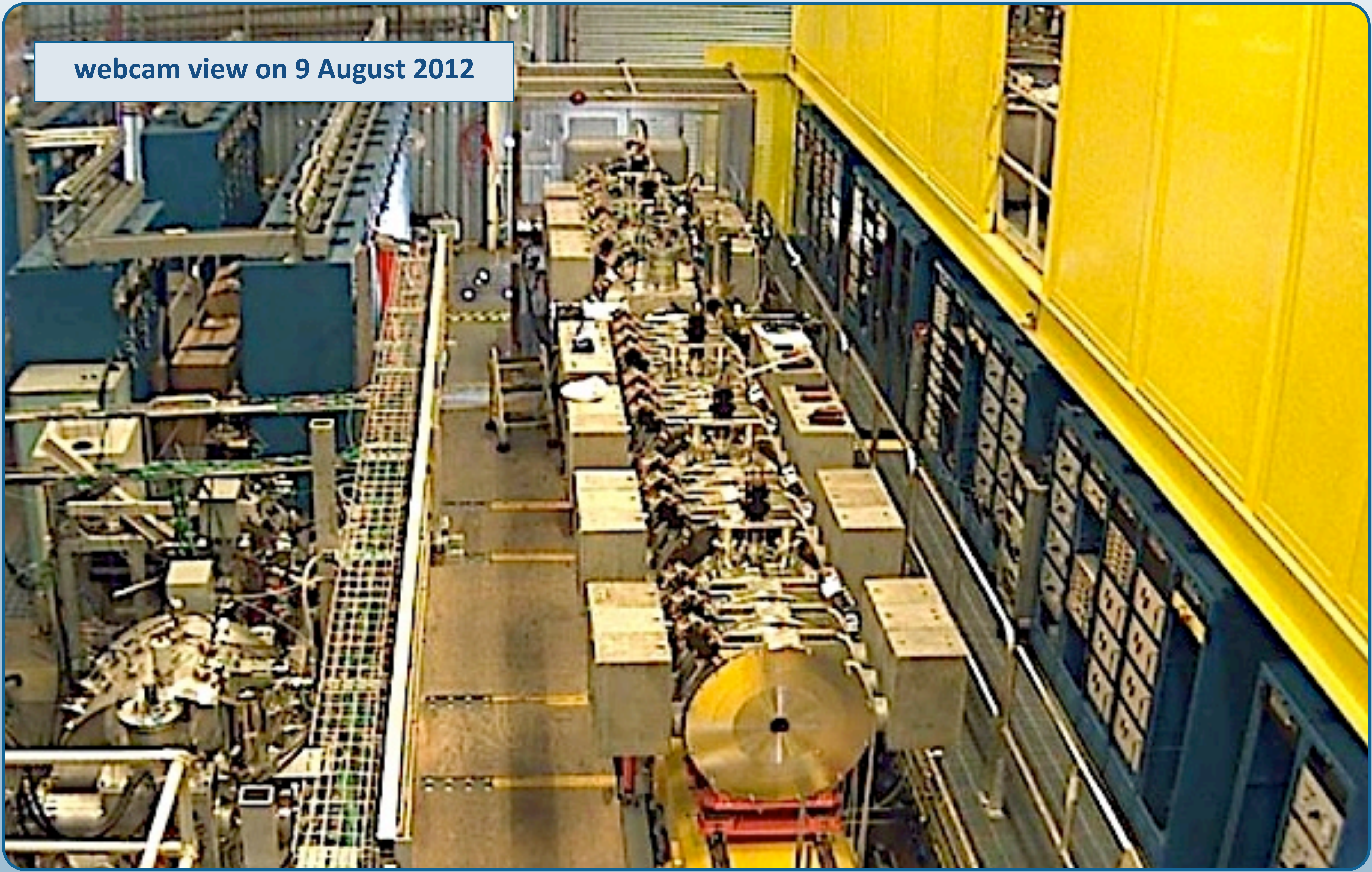
- commissioning is underway
- HEDP target experiments will follow



12-cell NDCX-II baseline layout



What does NDCX-II look like?



webcam view on 9 August 2012

Drift-compression is used twice in NDCX-II

initial non-neutral drift-compression for

- **optimum use of induction-core Volt-seconds**
- **early use of 70-ns 250-kV Blumlein power supplies from ATA**

inject → apply tilt → drift → accelerate → apply tilt → neutralized drift → target

final neutralized drift-compression to the target

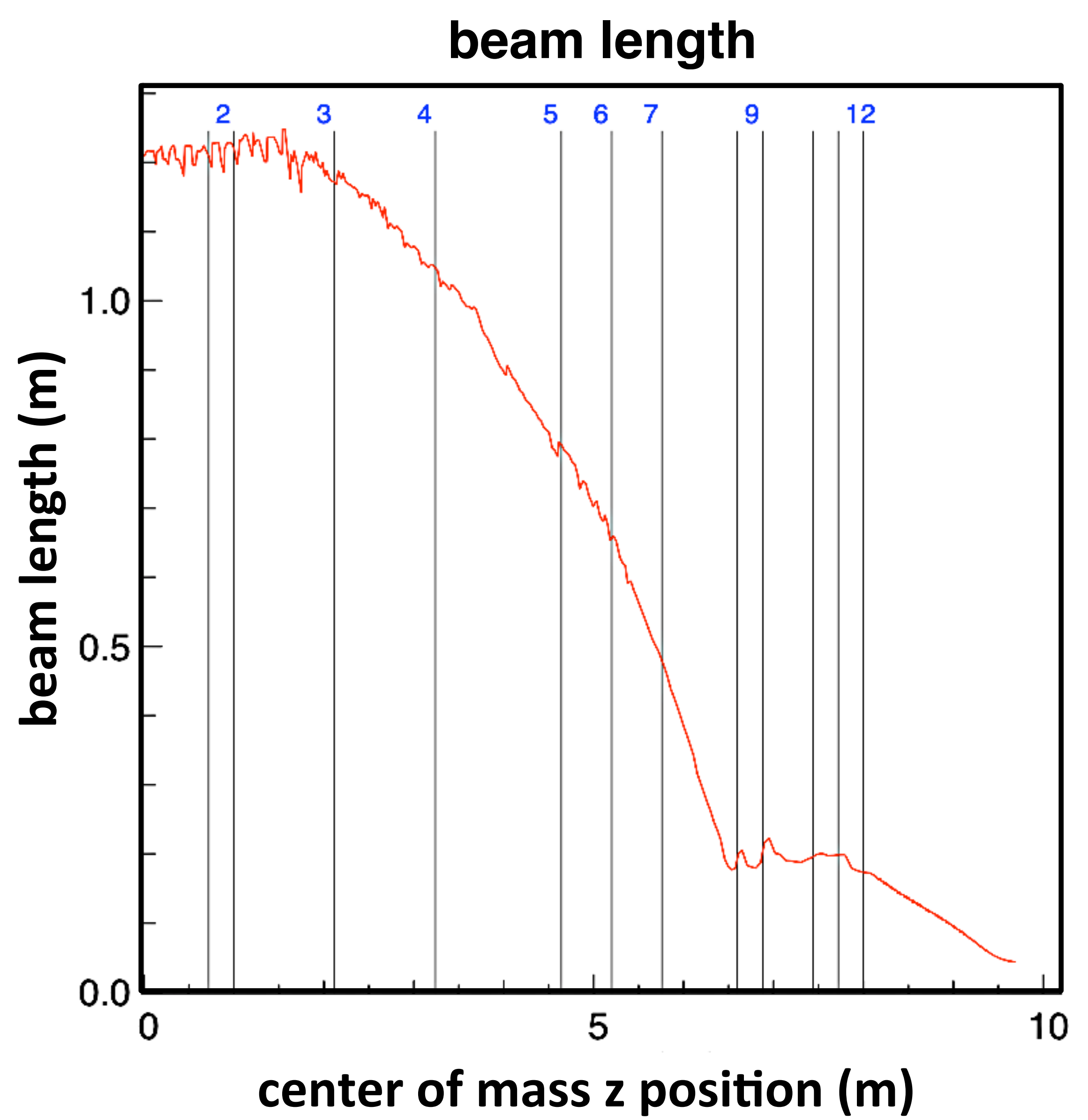
- **plasma electrons move to cancel the beam electric field**
- **requires $n_{\mathrm{plasma}} > n_{\mathrm{beam}}$ for this to work well**

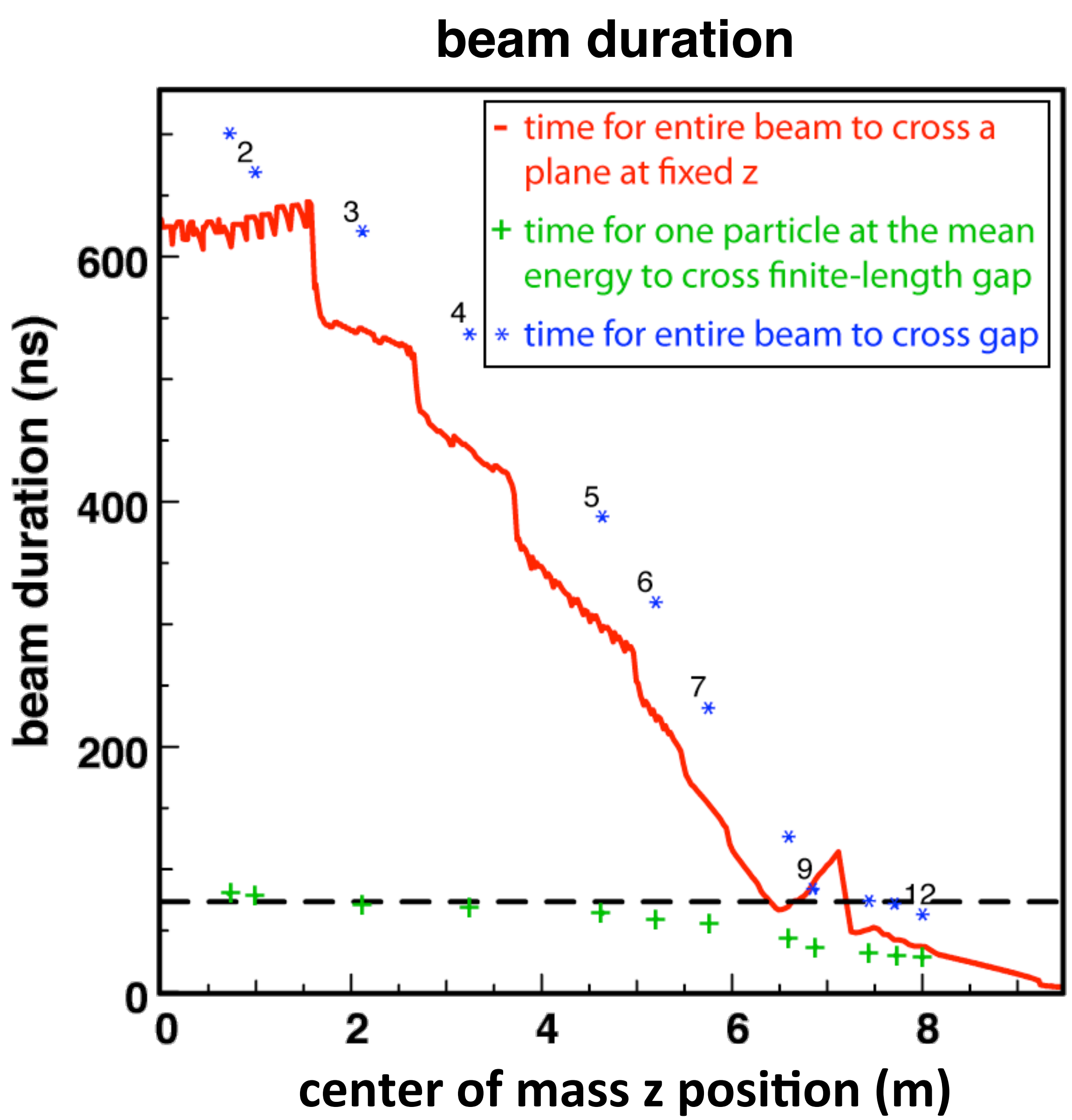
see A. Friedman, *et al.*, *Phys. Plasmas* **17**, 056704 (2010)

What does the baseline acceleration schedule look like?

NDCX-II uses a novel acceleration strategy to make best use of 70-ns ATA cells

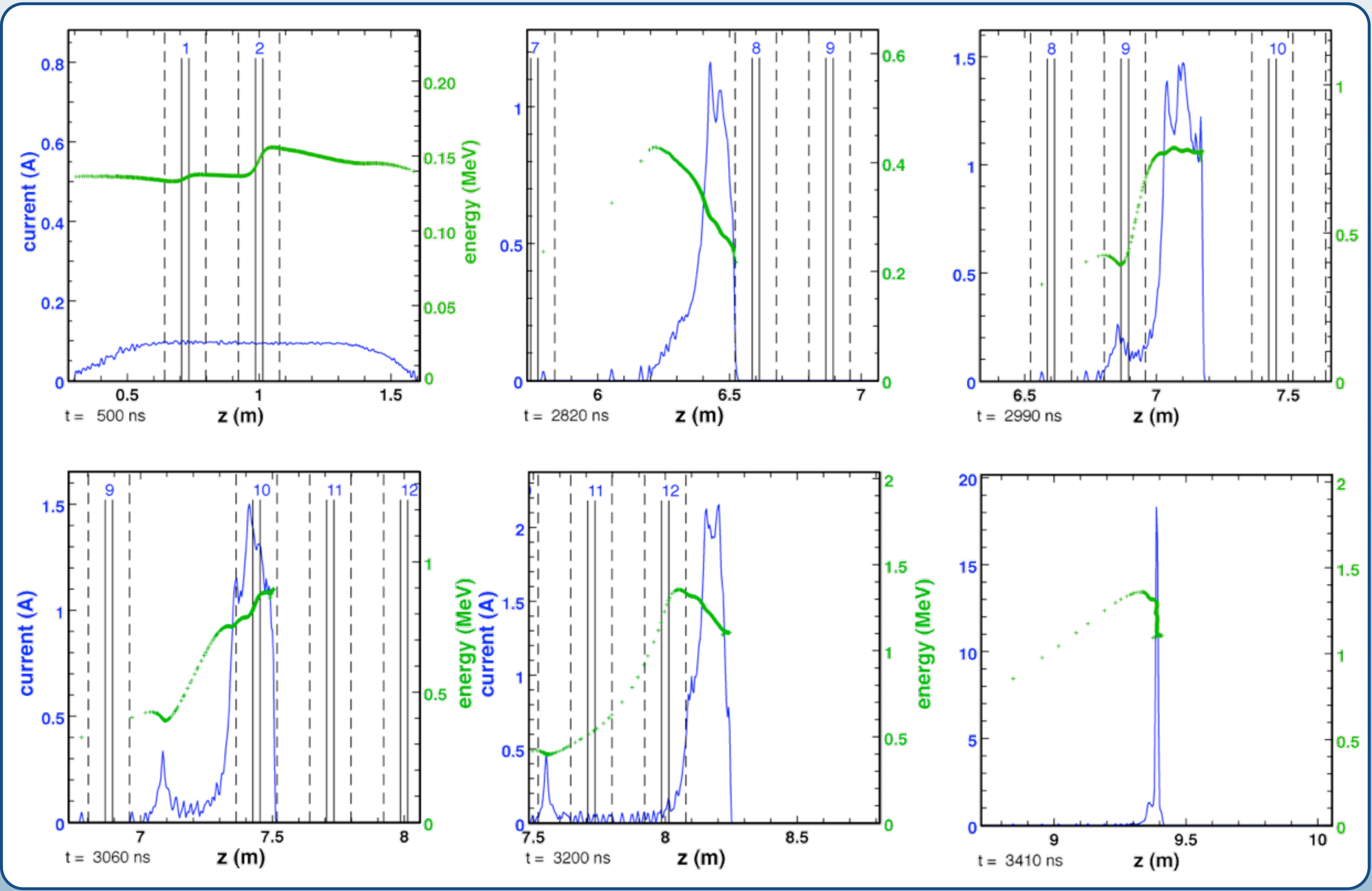
- upstream cells compress the beam
- the beam is allowed to “bounce” as remaining cells add energy and final velocity “tilt”





see A. Friedman *et al*, *Physics of Plasmas* **17**, 506704 (2010) for details

Beam snapshots illustrate acceleration schedule

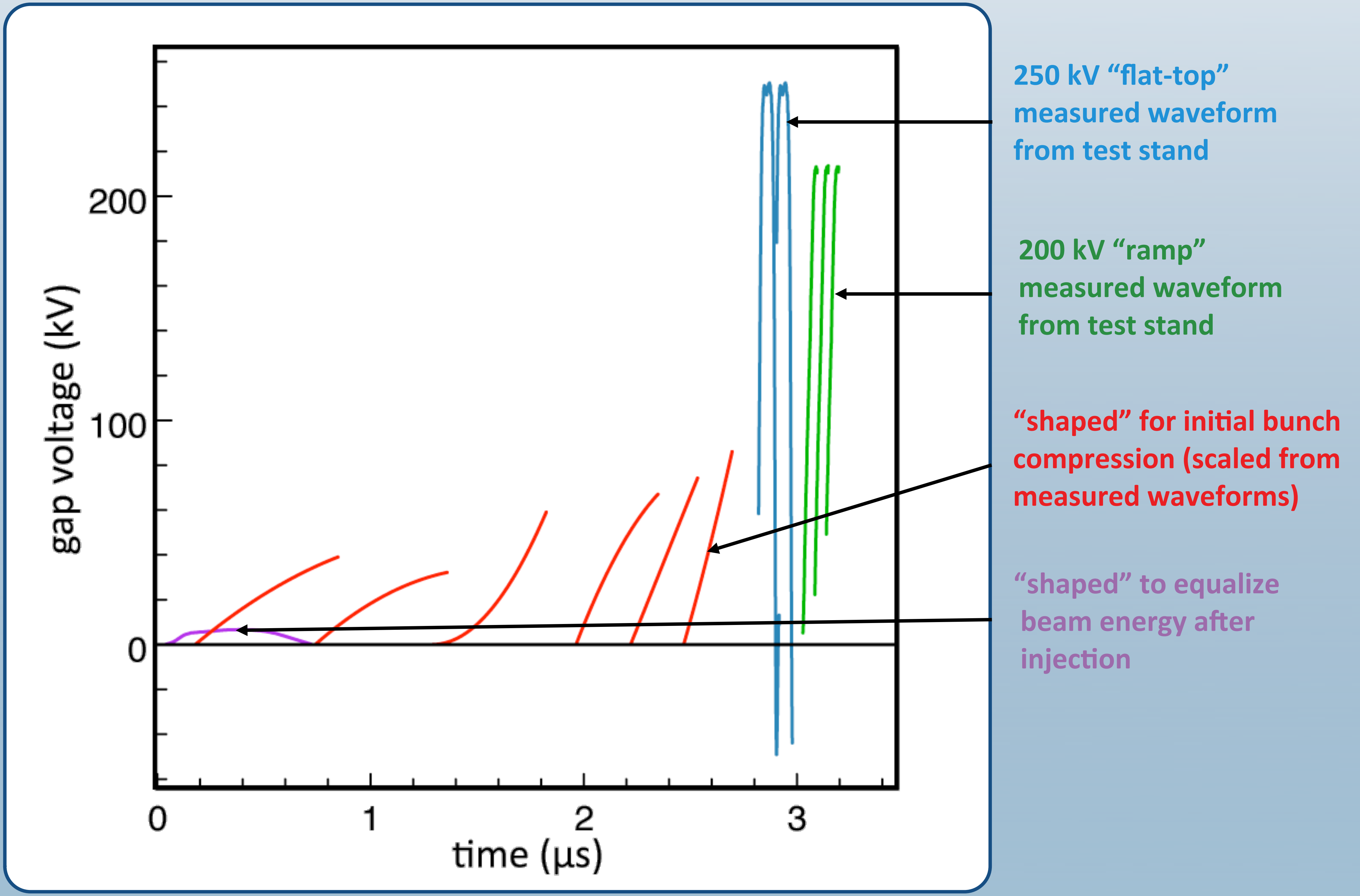


asp40g.024

What do the baseline fields look like?

strategy is to first compress the beam then accelerate it

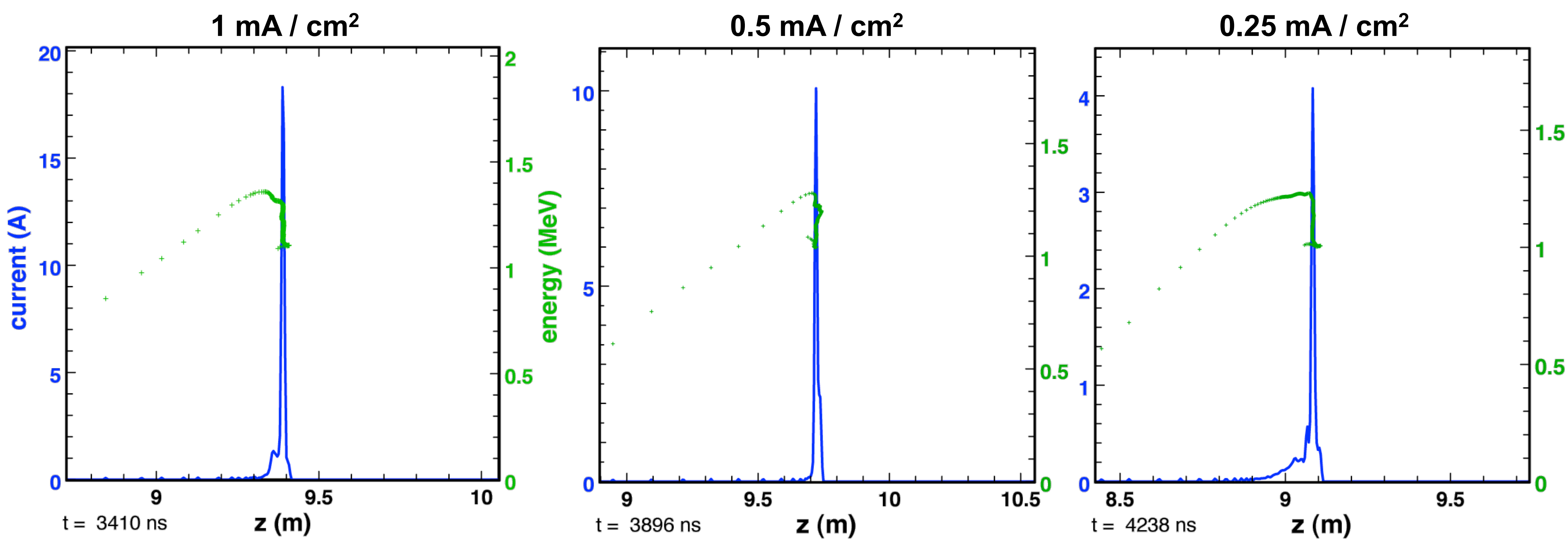
- **makes optimal use of ATA cores and Blumleins**



Scenario 1: reduce NDCX-II injection current to extend source lifetime

main complication is reduced space charge

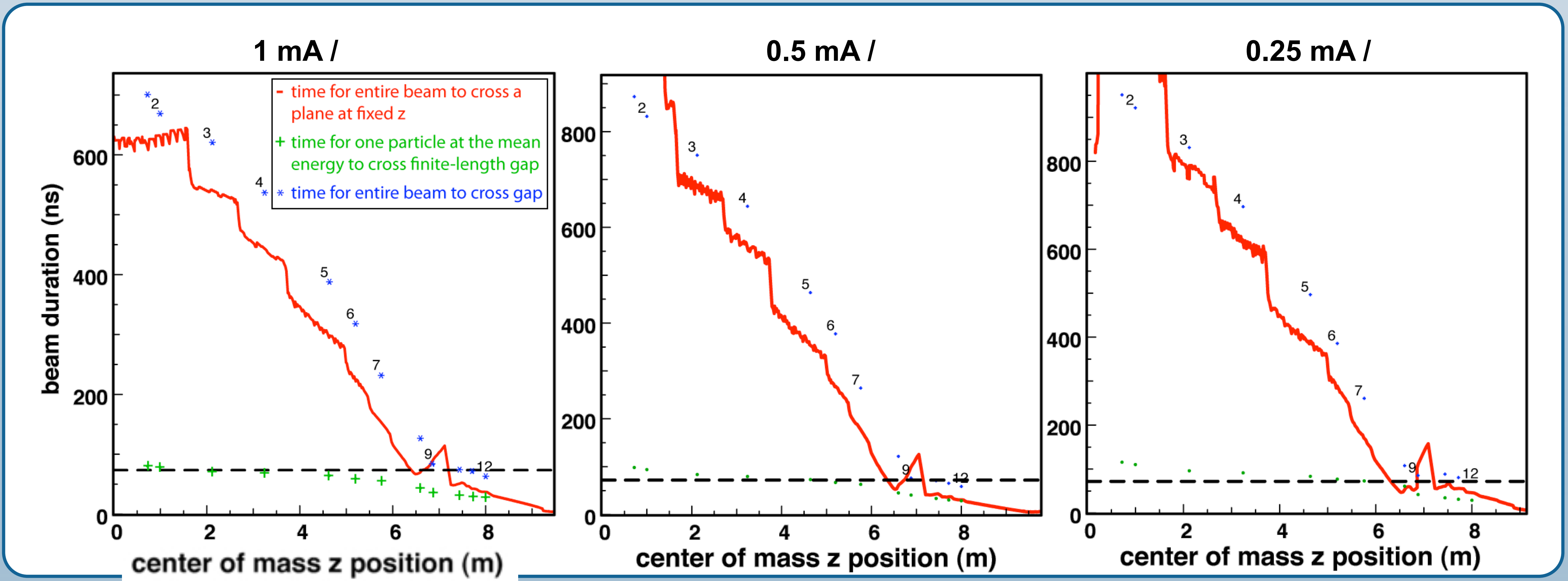
- emitter / extractor voltage ratio is held at 1.11
- waveforms in front end are only rescaled and retimed
- final currents scale roughly with source current



What do the acceleration schedules look like?

schedules remain similar after re-optimization

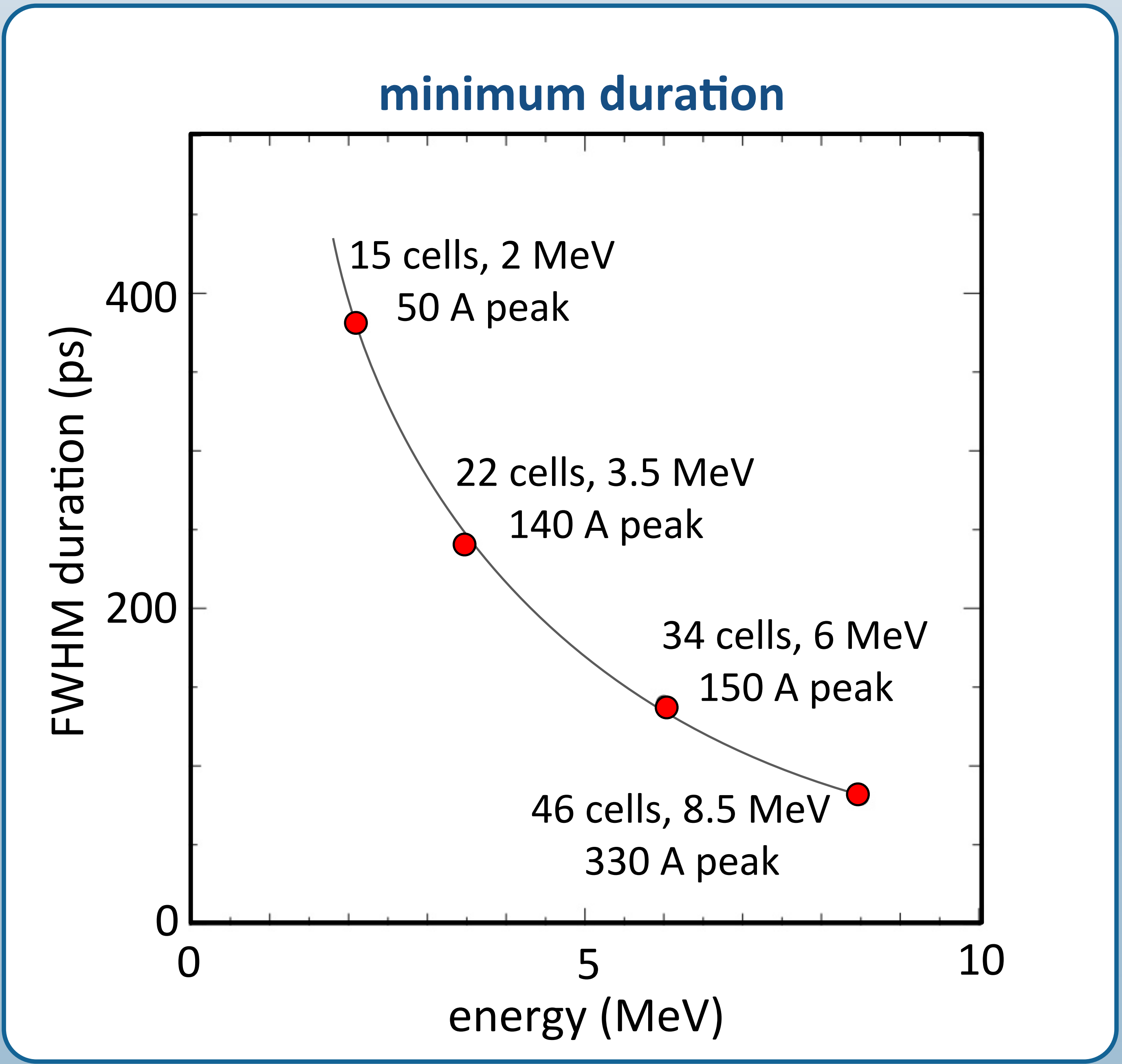
- cases here all use emitter/extractor voltage ratio of 1.11
- front-end voltages must be reduced to preserve fractional tilt



Scenario 2: add cells to reach higher energy

adding cells to NDCX-II will enable investigation of short ion pulses

- **50 ATA cells are available**
- **short pulses are needed to study direct-drive shock physics**

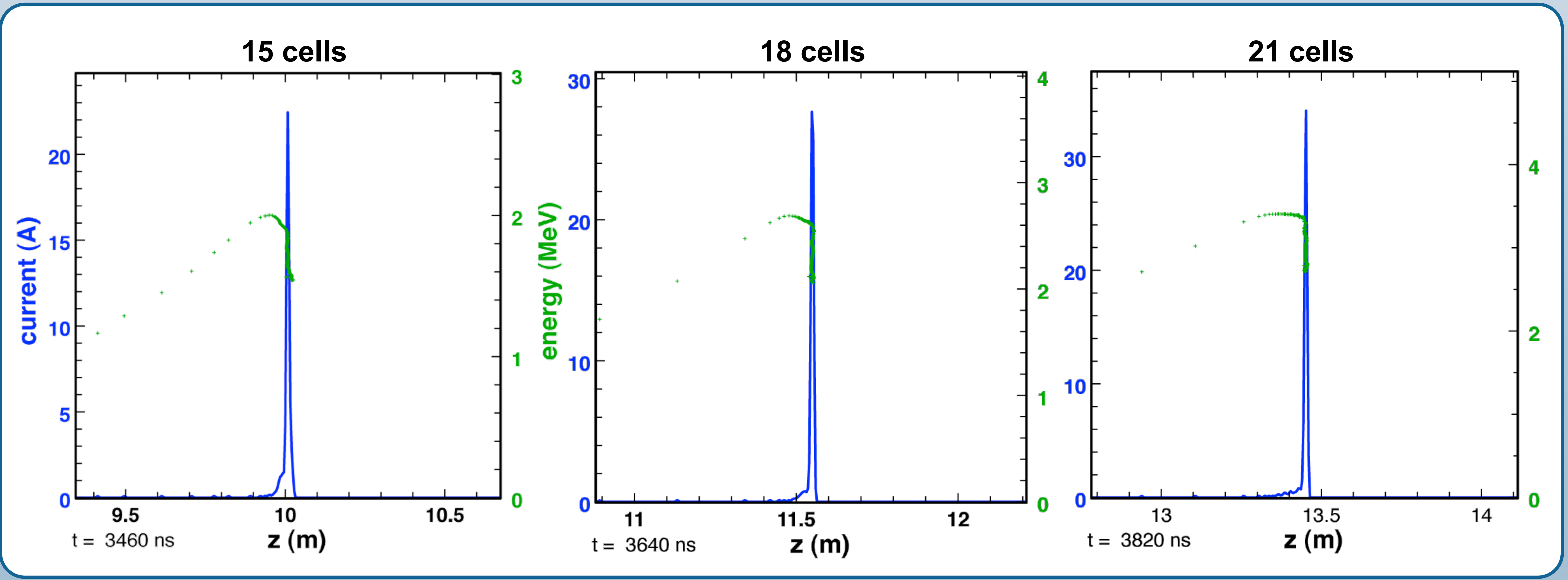


Warp simulations from D P Grote

How well does lengthening NDCX-II work?

each case needs to be re-optimized

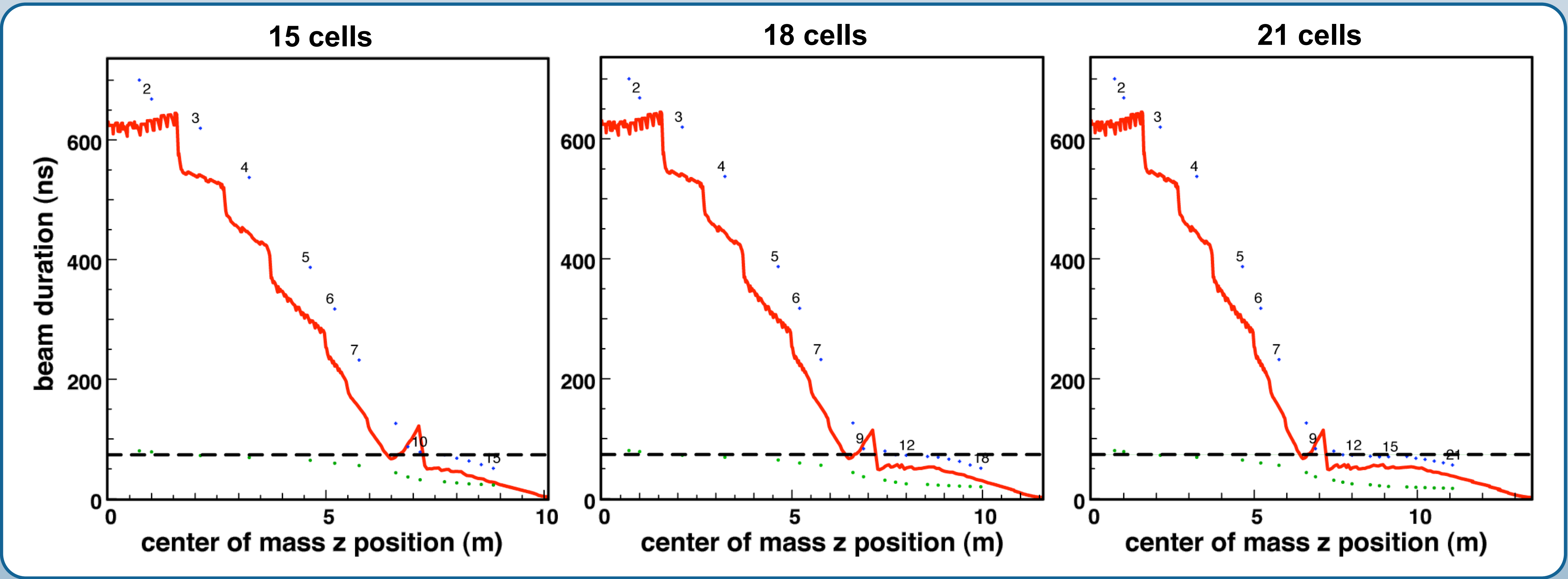
- front-end waveforms is unaltered from the baseline
- number of tilt cells is increased to give about 10% final tilt at the higher energy



What do the acceleration schedules look like?

beam all maintain nearly constant duration after initial compression

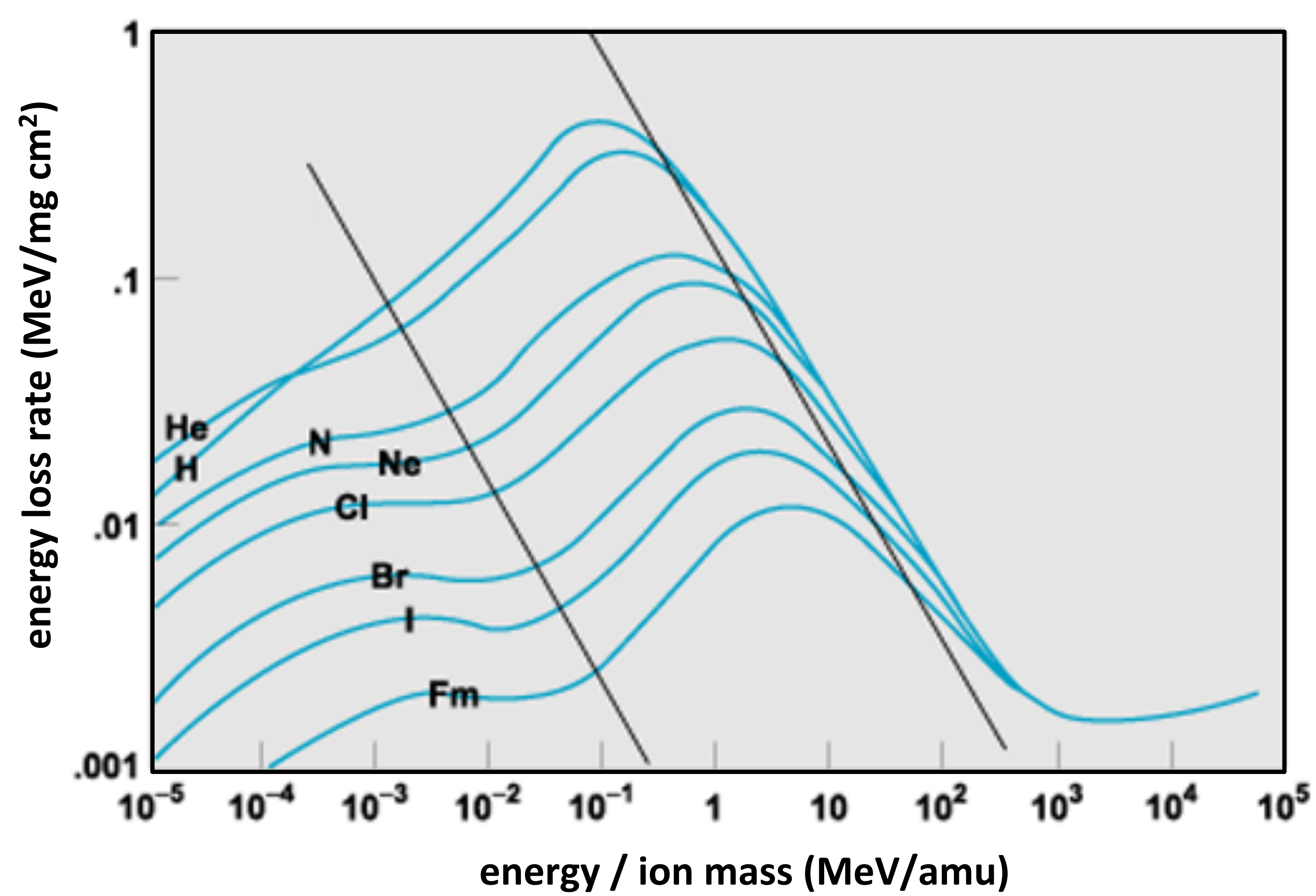
- corresponding length plots show increasing “bounce” after first minimum
- this lengthening smooths phase-space ripples



Scenario 3: use alternate ion species

other species may become attractive as NDCX-II matures

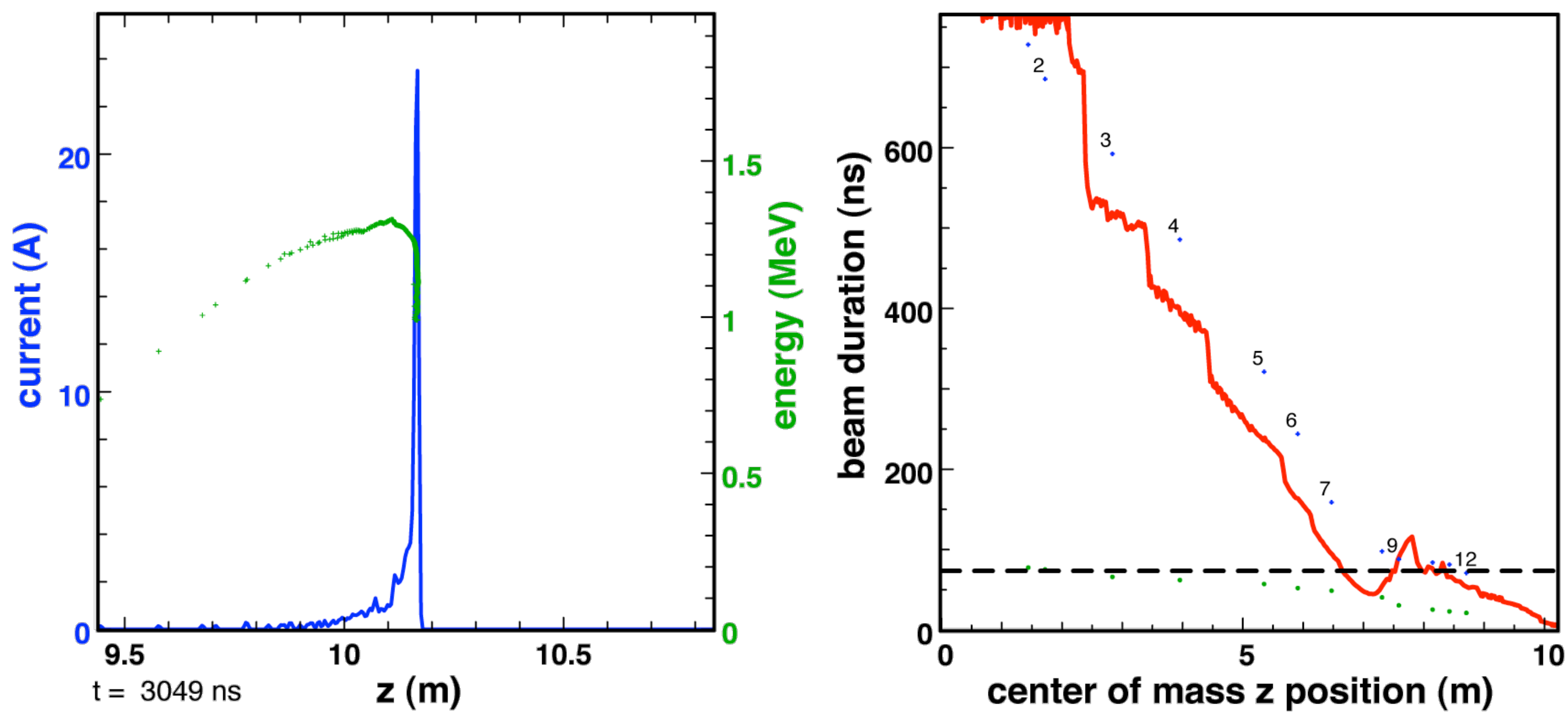
- a helium plasma source could replace lithium for higher current and longer life
- heavier species would allow Bragg-peak deposition at higher energies
- but most heavier species require a higher-voltage injector



Helium can use unmodified NDCX-II lattice

helium mass is sufficiently near lithium that NDCX-II voltages only need retiming

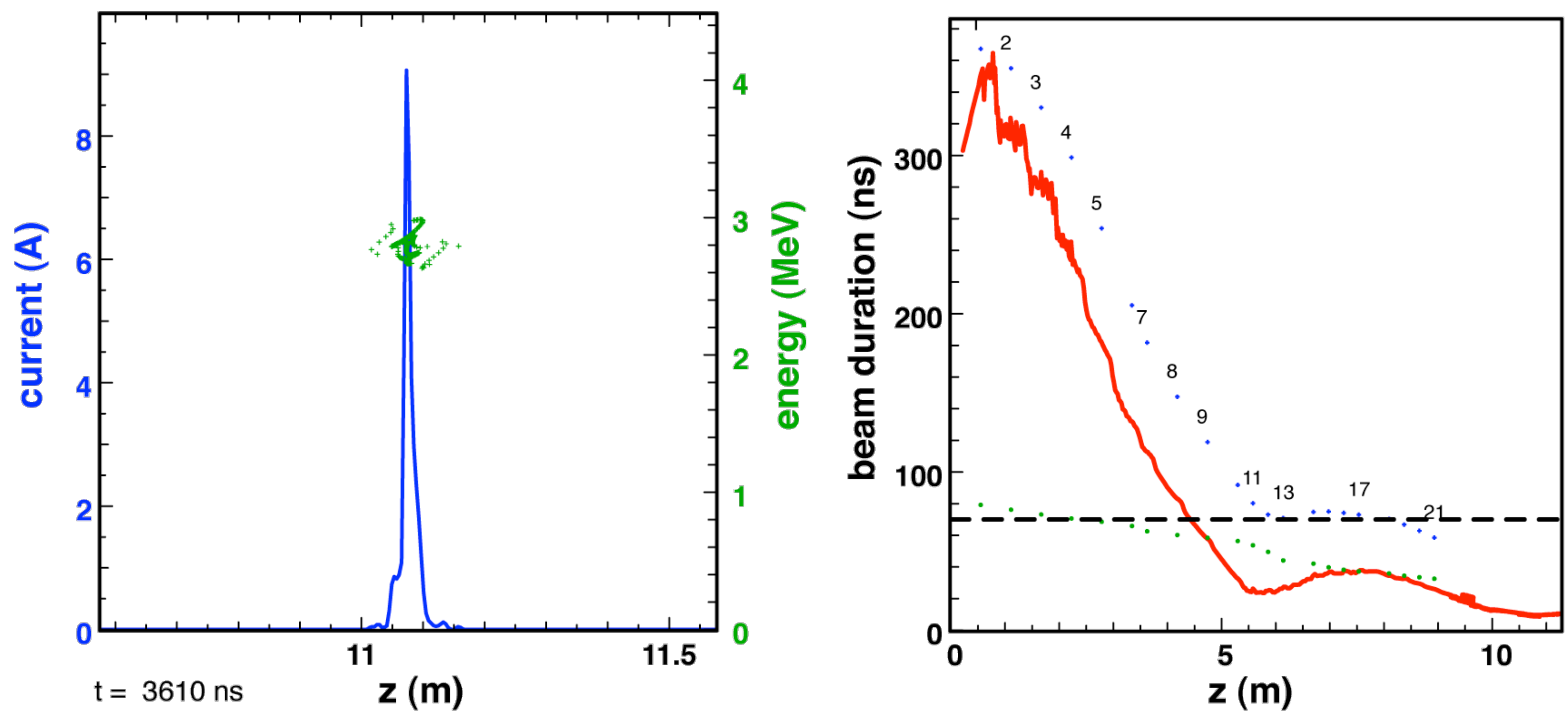
- **case shown assumes ideal beam with parameters set using zero-D code**



Sodium would require considerable modification of NDCX-II

sodium has 3.3 times the mass of lithium

- zero-D code scaling requires higher initial energy (430 kV)
- initial charge is halved and beam length is reduced by the mass ratio
- early ASP runs still require additional tilt cells for initial and final compression



Take-aways

US researchers are completing NDCX-II, a small, medium-energy induction accelerator

- use legacy induction modules from decommissioned electron machine ATA
- initial layout is expected to produce a space-charge-dominated beam of 1.2-MeV Li^+
- "Lego-block" design allows lattice to be easily reconfigured

energy can be increased to 9 MeV with available induction modules

- adding spare ATA cells offers a cost-effective pathway to higher energies
- increased fluence and reduced duration would make NDCX-II a better HEDP testbed
- no changes are needed to existing NDCX-II front end

current can be reduced to extend source lifetime

- lithium sources require high temperatures (1250-1275 °C) for full current
- source lifetime is expected to be 40 hours at that temperature
- reducing current during alignment and turning extends lifetime

using other ion species can allow Bragg-peak deposition at higher energies

- heavier ions require higher-energy source or more upstream acceleration
- usable scenarios still must be worked out

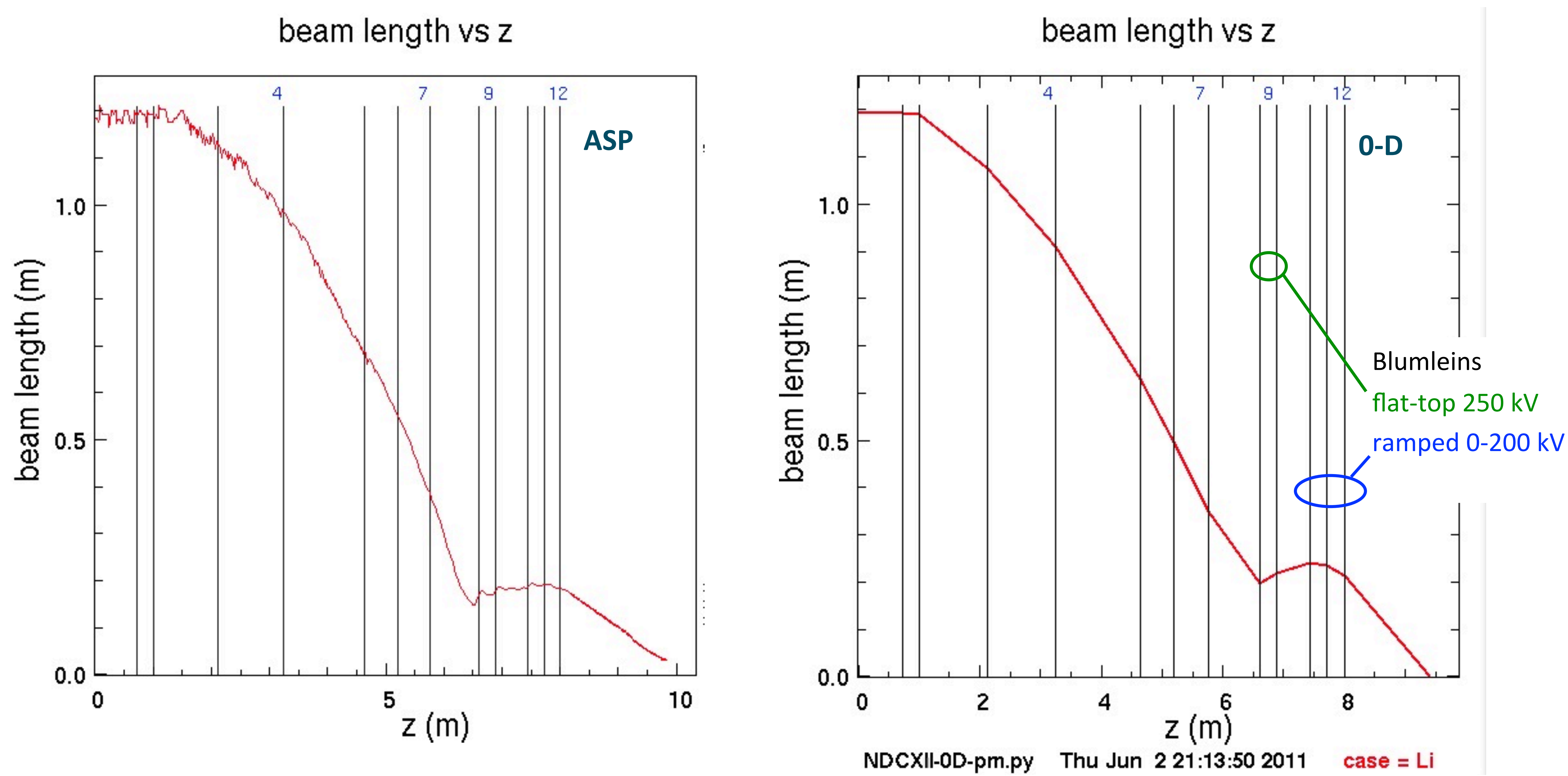
NDCX-II will have a large operating range

What is ASP-zero?

ASP-zero calculates a "0-D" approximation to NDCX-II acceleration schedules

essentially a Python spreadsheet developed in 2011 by Alex Friedman

- **tracks positions and energies of head and tail particles**
- **estimates effects of space charge from a constant-radius "g-factor" model**
- **main loop has just 14 lines of code**



Details of the model

beam head and tail kinetic energy is driven by two effects

- **applied voltages cause energy jumps in the gaps, treated here as instantaneous**
  - **head and tail gap voltages are taken from the NDCX-II reference design**
  - **pulse durations are adjusted as needed to accommodate faster or slower beams**
  - **the user may scale voltages in the compression section, as needed**
- **between gaps, space charge field accelerate head and decelerate tail**
  - **"g-factor" model is used, assuming a parabolic density profile**
  - **the space charge force is adjusted by an *ad-hoc* multiplier α to match ASP**

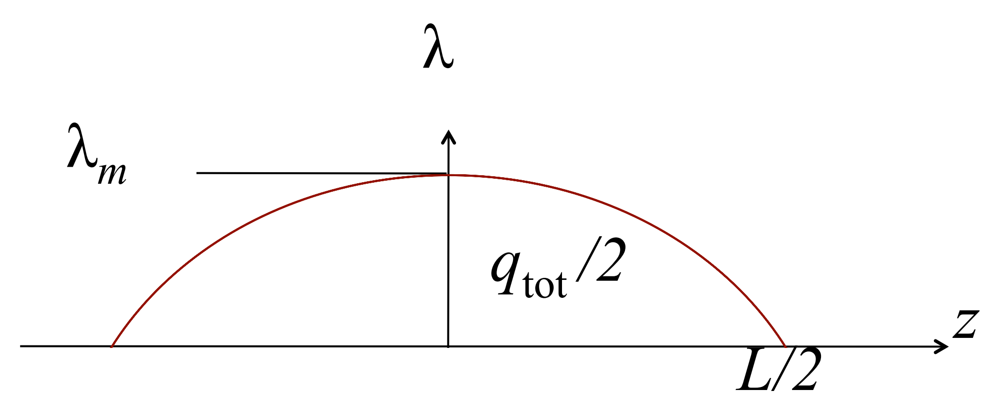
equations

$$\lambda(z) = \lambda_m \left[1 - \left(\frac{2z}{L}\right)^2\right]$$

$$\frac{q_{\mathrm{tot}}}{2} = \int_0^{L/2} \lambda(z) dz = \frac{\lambda_m L}{3}$$

$$\lambda_m = \frac{3}{2}\frac{q_{\mathrm{tot}}}{L}$$

$$\frac{d\lambda}{dz}(L/2) = -6\frac{q_{\mathrm{tot}}}{L^2}$$



$$g_0 = 1/2 + 2\log(r_{\mathrm{pipe}}/r_{\mathrm{beam}})$$

$$F(L/2) = -\alpha\frac{q_{\mathrm{ion}}}{(4\pi\epsilon_0)} g_0 \frac{d\lambda}{dz} = \alpha\frac{q_{\mathrm{ion}}}{(4\pi\epsilon_0)} g_0\, 6\frac{q_{\mathrm{tot}}}{L^2}$$

Consistency checks

transportable line charge

- assume matched Brillouin flow
- choose a maximum solenoid field B_{max} = 2.75 T
- verify that the calculated line charge is less than $\lambda_{\rm max} = \frac{\pi\epsilon_0 q_{\rm ion}}{2}\frac{(r_{\rm beam}B_{\rm max})^2}{m_{\rm ion}}$

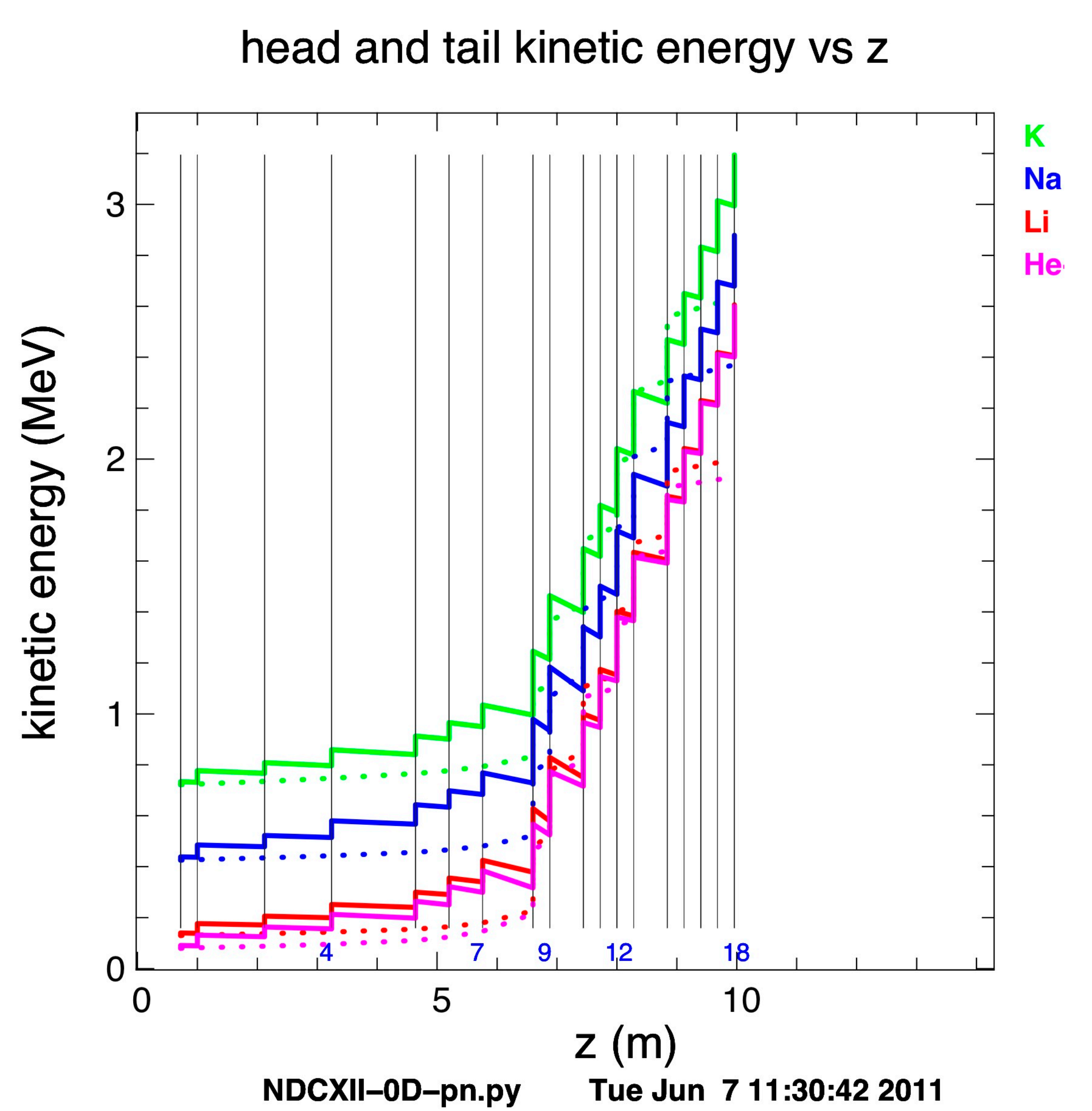
induction-cell volt-seconds

- ATA cells have demonstrated a 70 ns FWHM at 250 kV
- verify that the calculated waveform require less than 250 x 60 kV-ns = 0.015 V-s

ASP-zero has been tested with four ion species

minimal alteration was made in NDCX-II baseline configuration

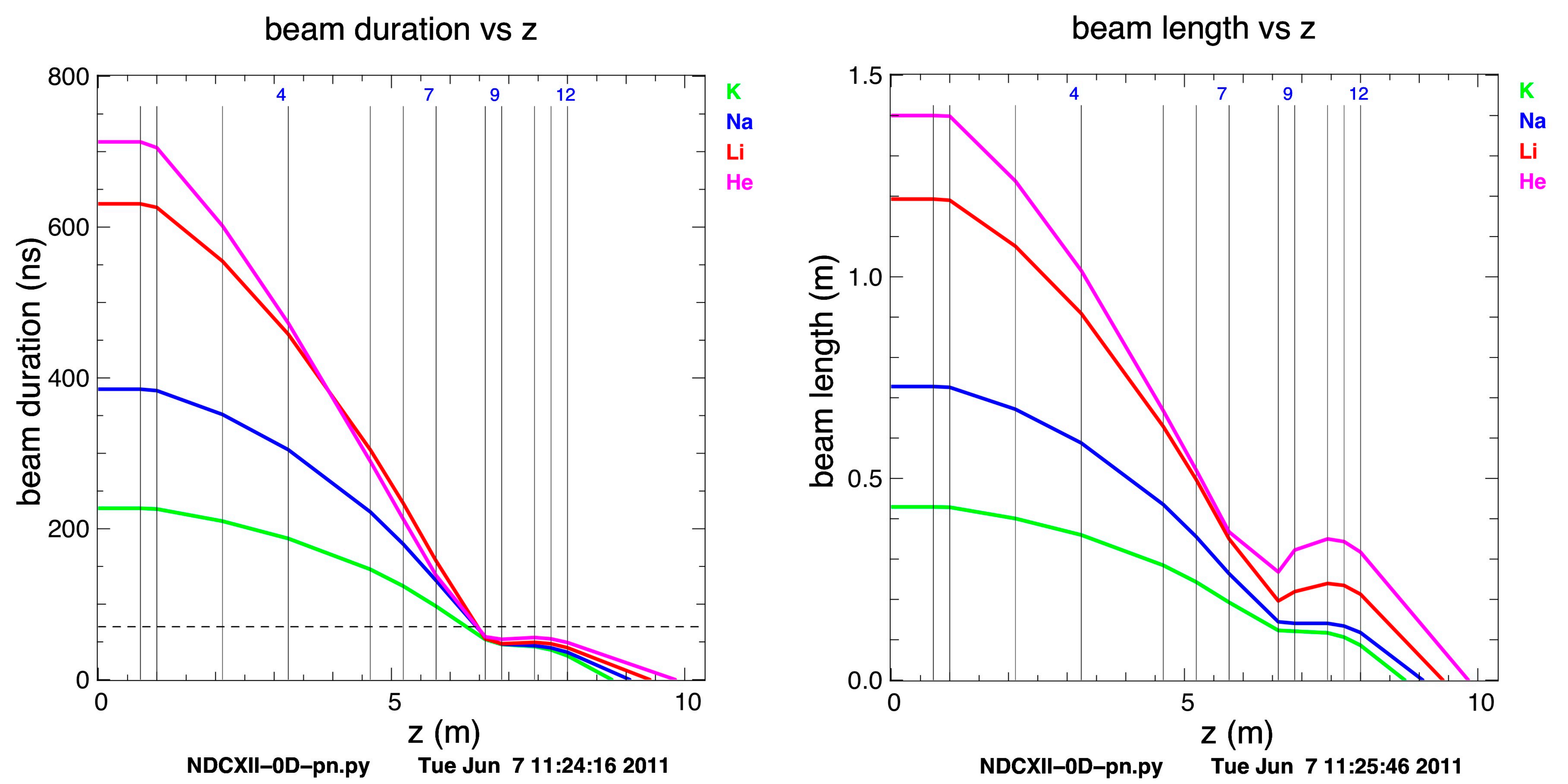
- physical layout of cells was unchanged
- initial energy was increased with mass to maintain the same initial velocity
- initial beam length decreased with mass to compensate for reduced fractional tilt



Acceleration schedules for four species are qualitatively similar

pulses are first compressed to stagnation, then allowed to expand

- final tilt voltages increase with ion mass to maintain similar velocity tilt at exit
- all cases stay within available volt-seconds limit
- Na^{+} and K^{+} exceed maximum transportable charge and may need stronger solenoids



Limitations of the model

ASP-zero provides a useful starting point for studying alternative NDCX-II species

but

ASP runs made with ASP-zero parameters show insufficient compression

- **parabolic model underestimates effects of space charge**
- **ASP designs waveforms more conservatively, reducing tilt added per cel**
- **adding more cells and drift space can lead to credible designs**

more design effort is needed to find optimum design points for Na^+ and K^+ ions